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Century to millennial-scale temperature variations for the last two thousand years indicated from glacial geologic records of Southern Alaska

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Abstract

Comparisons of temperature sensitive climate proxy records with tree-ring, lichen and radiocarbon dated histories from land-terminating, non-surging glaciers for the last two millennia from southern Alaska identify summer temperature as a primary driver of glacial expansions. Two major intervals in the Alaskan chronology of glaciation, during the First Millennium AD (FMA) and again during the Little Ice Age (LIA), are evident as broad times of cooling and ice expansion. These two intervals are respectively followed by ice retreat coincident with the Medieval Warm Period (MWP) and contemporary warming, and together correspond with millennial-scale variations recognized in the North Atlantic. The FMA advance appears to be of similar extent as the subsequent LIA expansions indicating a uniformity of forcing over the past two millennia.
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1. Introduction

Reductions in glacier volume are often cited as among the strongest evidence of recent multi-decadal global warming (Dyurgerov and Meier, 2000; Folland et al., 2001) and glacier length variations have been used to directly estimate past temperature change (Oerlemans, 2005). In addition to being sensitive indicators of warming, glaciers along the southern Alaskan coast and near-coastal regions are significant contributors to contemporary sea level rise (Arendt et al., 2002). Therefore, glacial geologic records from this maritime region are an important paleoclimate record for understanding climate change over recent millennia and its linkages with the oceans.

Multiproxy reconstructions by Mann et al. (1999), Mann and Rutherford (2002) and Moberg et al. (2005) show that various high and low resolution time series spanning the last 2000 years can be combined into

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temperature reconstructions in an effort to capture the amplitude and variance of climate change. These reconstructions reveal the major late Holocene climate episodes such as the Medieval Warm Period (MWP) and Little Ice Age (LIA); however, there is significant variability in the amplitude of change (Esper et al., 2005) and regional timing of response (D'Arrigo et al., 2006) to these episodes. None of these reconstruction efforts have yet used glacier variations as an indicator of temperature variability.

Glacier response to climate change during the LIA in northwestern North America has been well documented along the Alaskan Kenai, Chugach, Wrangell and St. Elias mountain ranges (Wiles and Calkin, 1994; Wiles et al., 1999, Calkin et al., 2001; Wiles et al., 2002, 2004). Glaciers in these ranges were also included with termini histories from the Canadian Rockies and Coastal Ranges of British Columbia to identify a First Millennium AD (FMA) interval of expansion (Reyes et al., 2006). In this paper we update and extend this previously published work with new data from five termini, and then consider the broader climatic context of the composite southern Alaskan glacial record. The new information includes tree-ring ages from Bear Glacier, which updates a previous report (Wiles and Calkin, 1994) and moraine ages from Marathon Cirque near Seward, Alaska both sites on the Kenai Peninsula (Fig. 1). We also report on new tree-ring and moraine ages from College Fiord, Prince William Sound at Amherst and Crescent Glaciers and radiocarbon data from Yakutat Glacier located 20 km east of Yakutat (Fig. 1).

2. Study area and dating methods

The Kenai, Chugach and St. Elias mountain ranges form an almost unbroken chain of 2000 to 6000 m peaks around the northern Gulf of Alaska (Fig. 1). This topographic barrier intercepts moist maritime air from the south, with the result of heavy precipitation and the development of extensive icefields and valley glacier complexes. The Wrangell Mountains are in a transitional interior area with correspondingly less precipitation and less extensive glacierization.

Ice margins in this region have repeatedly advanced into forests on their forefields during the late Holocene, and dates from these preserved plant remains form the basis of reconstructed termini histories. Cross-dated tree-ring records from glacially killed trees (e.g. Wiles et al., 1999) provide the most precise dates and are possible for well-preserved logs up to ~ 1000 years old (Figs. 2, 3). Radiocarbon (^{14}C) ages are used for older logs or organic materials that are unsuitable for tree-ring analysis. Radiocarbon ages are reported here in two ways. First, where a unique date is needed we use the weighted average of the calibration probability

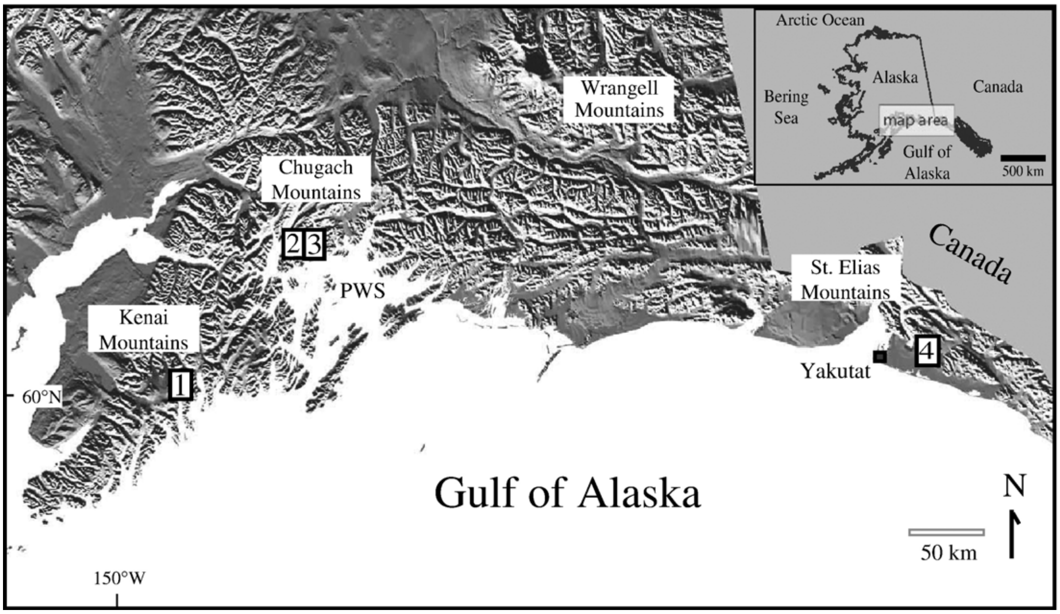

Fig. 1. Mountain ranges and glacier locations for southern Alaska. 1 — Bear Glacier and Mount Marathon Cirque, Kenai Peninsula; 2, 3 — Crescent and Amherst glaciers, College Fiord, Prince William Sound (PWS); 4 — Yakutat Glacier, west of Yakutat.

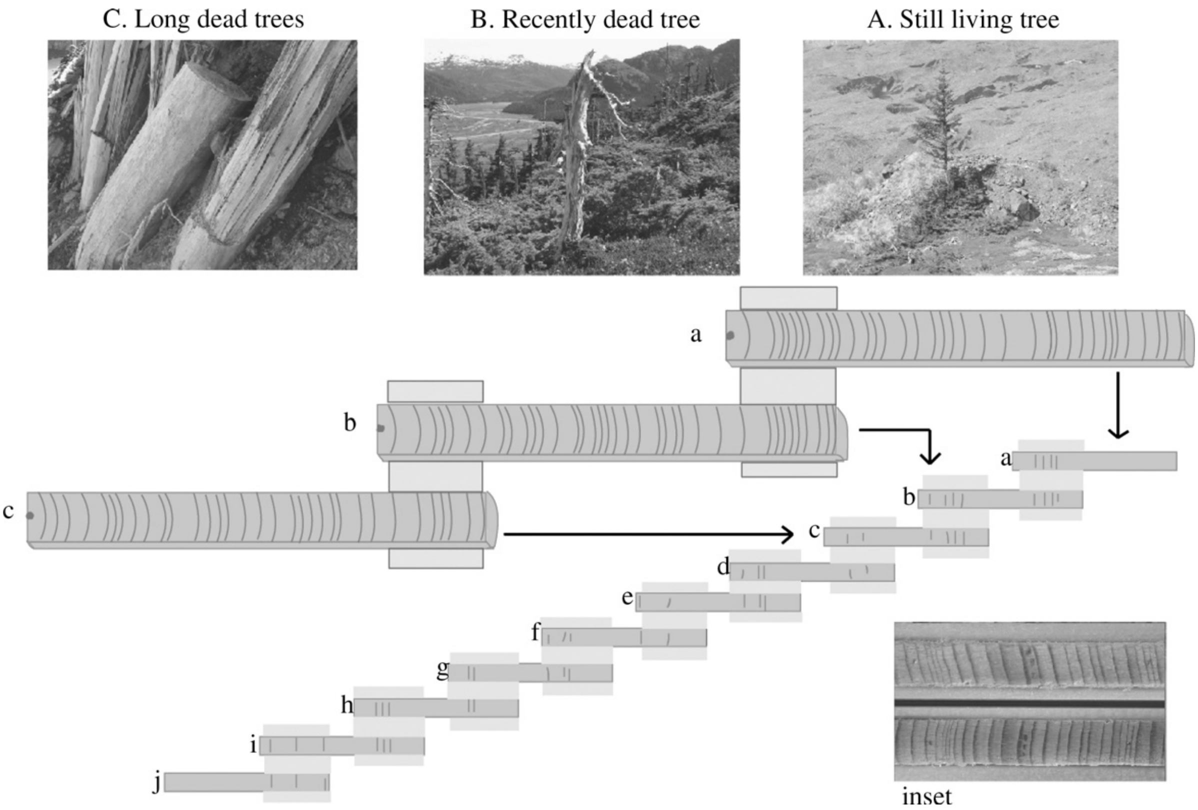

Fig. 2. Tree-ring cross dating is a primary tool in building glacial histories in Southern Alaska. Floating ring-width series are constructed from wood collected in glacier forefields. These floating ring-width chronologies are then dated with series from living and recently dead trees to assign calendar dates. Lower right inset shows two cross-dated tree cores; cross dating was done visually and with the aid of the COFECHA cross-dating computer program (Holmes, 1983; Grissino-Mayer, 2001).

distribution function (Telford et al., 2004). Second, we consider the 2σ range of calibrated years AD (Fig. 4; Table 1) when discussing and presenting ages that may be equivalent. Calibration was done using CALIB (Stuiver and Reimer, 1993; Reimer et al., 2004) and all calibrated ^{14}C values are rounded to the nearest decade (Table 1).

Dates of ice retreat are based on colonization of moraines by trees and lichen. First generation trees were dated by ring counts and then adjusted to an ice margin retreat date using an ecesis time of 15 years (e.g. Wiles et al., 1999). The largest lichen were measured to the nearest millimeter and converted to an age estimate using the most appropriate regional calibration curve (Denton and Karlèn, 1973; Wiles and Calkin, 1994; Wiles et al., 2002).

3. Individual glacier histories

We present here five new or updated glacier histories based on field and laboratory work over the past decade. Discussion begins in the Kenai Mountains (Fig. 1) and progresses to the east.

3.1. Bear Glacier

Bear Glacier is a 30-km long outlet tongue from the Harding Icefield in the central Kenai Mountains (Fig. 1). Since its retreat from the Little Ice Age (LIA) terminal moraine, a major proglacial lake has developed at the terminus into which the ice margin calves icebergs.

Previous work here (Wiles and Calkin, 1994) was based on radiocarbon ages from detrital wood (Table 1) collected in a drained lake basin and tributary valleys along the eastern side of the forefield. Since our earlier studies, we have cross-dated logs that are accumulated in a drained proglacial lake that was dammed when ice advanced. The last years of recorded growth were around AD 1604; however, the logs were badly abraded and so these trees likely died in the decades after this date as the ice margin advanced. Based on tree ages on the outer moraine (Wiles and Calkin,

Fig. 3. A glacially overrun forest from the Land Lobe Glacier in Columbia Bay, Prince William Sound. These hemlock forests were overrun by ice during the LIA. Two people in the lower middle foreground provide scale.

1994), the terminus reached its LIA maximum before AD 1888.

3.2. Marathon Mountain Cirque

This small cirque glacier is situated immediately west of the town of Seward in the Kenai Mountains (Fig. 1). A moraine complex with three distinct ridges encircles a small pond at about 700 m a.s.l., and an inactive rock glacier extends farther down valley to the northeast. Diameters of the largest lichen on the three moraine ridges were measured and found to be, respectively, 90, 67 and 40 mm. Using the Kenai Mountains lichen growth curve (Wiles and Calkin, 1994) gives dates of AD 1750, 1812 and 1885 for stabilization of these ridges.

3.3. Amherst and Crescent glaciers

Crescent and Amherst glaciers are land-terminating valley glaciers located in the Chugach Mountains along the eastern flank of College Fiord (Fig. 1). They are independent ice masses that flow northwest; however, during the LIA their ablation areas may have coalesced with that of nearby Lafayette Glacier. Forested moraines within 10 m of sea level mark their most recent maxima and well-preserved subfossil logs were found within moraines on both their forefields.

At Amherst Glacier, tree-ring dated logs at two sites immediately in front of and within the outer moraine have outer ring calendar dates of AD 1633 (Miller, 1998), and ages of trees growing on the outermost moraine indicate stabilization in AD 1830. The terminus has retreated about 2.6 km since its LIA maximum and currently terminates in a proglacial lake that formed sometime before 1935.

The terminus of Crescent Glacier is also retreating and is currently almost 2 km up-valley from its outermost moraine. Cross-dates of glacially killed trees on the forefield show that the margin was advancing in AD 1625 (Johnson et al., 2006). The outer moraine stabilized in about AD 1780 and two inner moraines, also dated with tree-rings, were ice-free in 1807 and 1935 respectively.

3.4. Yakutat Glacier

Yakutat Glacier is a 19 km long, south-flowing ice tongue to the east of the town of Yakutat (Fig. 1). The névés of this system in the Brabazon Icefield have dramatically lowered during the past 100 years and almost this entire glacier may vanish in the next century (A. Post, in press). The terminus currently calves icebergs into Harlequin Lake that, in turn, drains into the nearby Gulf of Alaska via the Dangerous River.

The First Millennium AD (FMA) expansion of Yakutat Glacier is defined by five radiocarbon ages on wood. Four samples from till and ice-proximal glacio-lacustrine sediments near the current terminus had ages of cal. AD 750, 800, 800 and 890. The fifth sample, with an age of cal. AD 700, was from a tree buried in alluvium along the Dangerous River. Considered together these dates show that glaciofluvial aggradation preceded a major advance during the FMA and that the Harlequin Lake basin may not have existed until very recently, a situation similar to that of the southern end of the adjacent Russell Fiord basin (Barclay et al., 2001).

Continued expansion or readvance during the LIA is indicated by an age of cal. AD 1250 from another log buried in alluvium along the Dangerous River and a terminal moraine that rims Harlequin Lake. Tree ages at 300 m elevation along the western margin of the forefield suggest that the ice filling the Harlequin Lake basin was thinning by AD 1781 or before, while the oldest tree on the LIA terminal moraine shows retreat of the ice margin by 1886. This latter date is consistent with the observation by Tarr and Martin (1914) that the glacier terminus was shrunken but still covering all of what is now Harlequin Lake in 1895.

4. Synthesis of glacial records

Factors such as microclimate, response time, surging and iceberg calving can all complicate climatic interpretation of individual glacial histories. Also, the geologic and

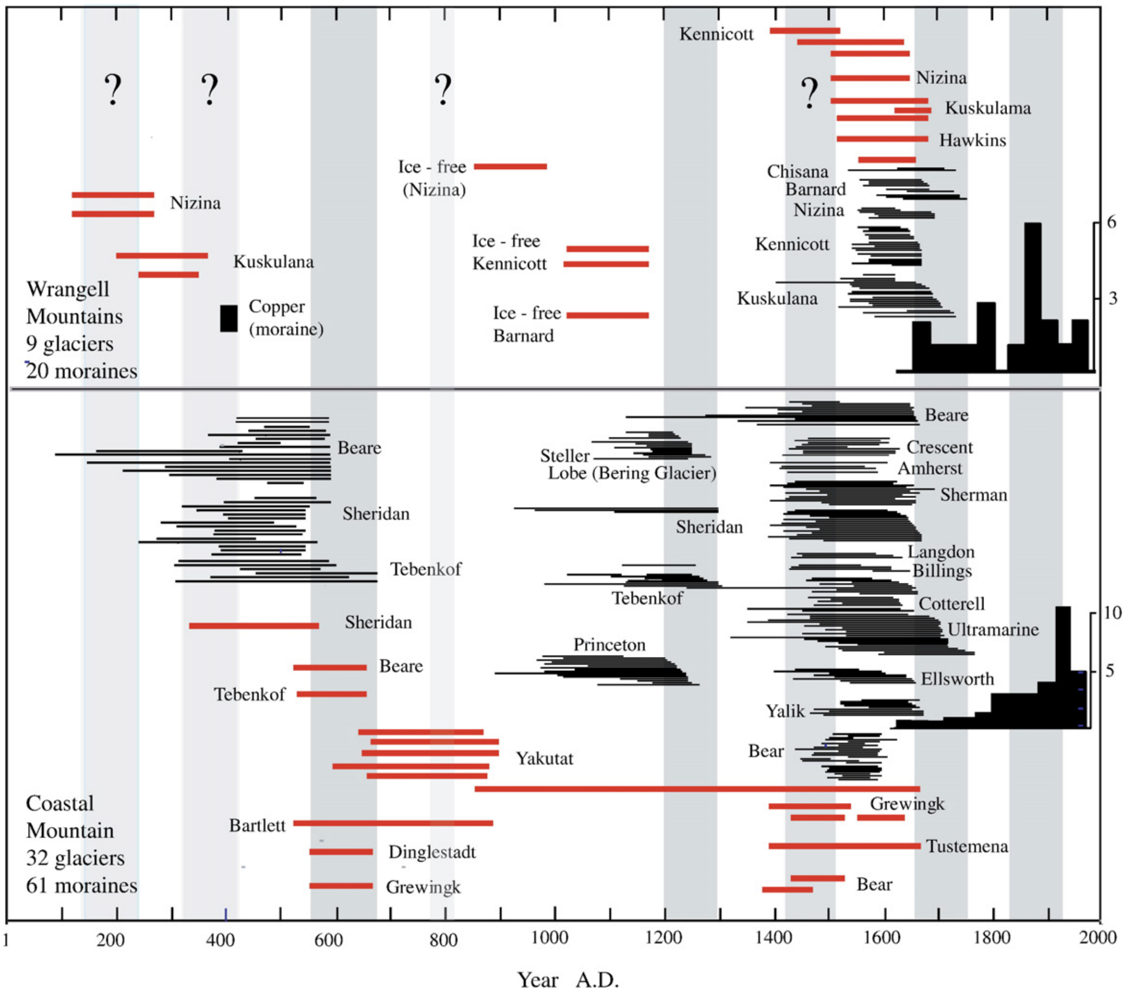

Fig. 4. Compilation of radiocarbon ages (thick bars), moraine ages (histograms) and cross-dated forests (clusters of thin bars). Shaded intervals are times of general glacier advance. Shaded intervals with question marks are based on three or fewer glacier chronologies. This diagram includes the newly compiled C-14 and tree-ring dates from Yakutat, Crescent, Amherst and Bear Glaciers as well as moraine ages from Marathon Cirque, Crescent and Amherst.

geomorphic record of older advances is often fragmentary due to erosion and deposition by more extensive recent expansions. It is therefore important to consider the composite record from many termini when interpreting climate change from glacier histories. Here, we synthesize the histories of termini in, respectively, the coastal (Kenai, Chugach and St. Elias) ranges and the Wrangell Mountains to provide a southern Alaskan composite glacier record.

4.1. First Millennium AD (FMA) expansion

Six forefields in the Kenai, Chugach and St. Elias mountains show evidence of First Millennium AD (FMA) advances. A radiocarbon age of cal. AD 430 from a glacially killed tree at Sheridan Glacier (Tuthill et al., 1968) provides the earliest evidence of ice margin expansion. Additional logs in till and outwash at Sheridan, plus logs at Grewingk, Dinglestadt, Bartlett, Tebenkov, and Bear glaciers date the main interval of FMA advance to between cal. AD 590 and 650 (Reyes et al., 2006; Fig. 4). Many of these logs have been cross-dated to form floating chronologies that show multiple episodes of outwash aggradation within the FMA and decadal-scale differences in timing of termini advance. At several forefields these FMA expansions were almost as extensive as the subsequent LIA expansions.

In the Wrangell Mountains, radiocarbon and lichen ages indicate advance of three glaciers during the FMA (Wiles et al., 2002). Many white spruce logs are preserved below outwash and till at Kuskulana Glacier,

Table 1
Selected radiocarbon ages from southern Alaska[a]

^{14}C age (years BP)	Calibrated age range (years AD)	Laboratory number	Description and significance	Reference
Bear Glacier 1480±70	430–660 **560**	Beta-95990	In-situ stump in till	Johnson et al. (1997)
Sheridan Glacier 1610±100	230–640 **430**	I-1986	Glacier pushed log	Tuthill et al. (1968)
Nizina Glacier 1140±60	720–740 770–1020	Beta-122974	Transported alder in soil	Wiles et al. (2002)
1810±60	130–260 **200**	Beta-122976	Organic-rich Sediment in	Wiles et al. (2002)
320±50	1460–1650 **1560**	Beta-122973	Log buried in gravels	Wiles et al. (2002)
1810±70	70–390 **210**	Beta-122976	Organic-rich Sediment in	Wiles et al. (2002)
Hawkins Glacier 270±50	1470–1680 **1620**	Beta 133801	Log buried in till	Wiles et al. (2002)
Barnard Glacier 930±60	1010–1220 1110	Beta-133803	Wood in lateral moraine	Wiles et al. (2002)
Kuskulana 1720±60	130–340 **320**	Beta-133814	Organic-rich Sediment in	Wiles et al. (2002)
1760±60	130–410 **270**	Beta-133815	In-situ stump beneath till	Wiles et al. (2002)
410±60	1420–1530 1540–1640	Beta-133817	In-situ stump beneath till	Wiles et al. (2002)
270±60	1460–1680 1730–1810	Beta-133816	In-site stump in till	Wiles et al. (2002)
240±60	1480–1700 1720–1820	Beta-133813	In-site stump in till	Wiles et al. (2002)
Kennicott Glacier	1040–1260 **1160**	Beta-83680	In-site stump in till	Wiles et al. (2002)
990±60	950–1190 **1060**	Beta-133808	Stump in growth position	Wiles et al. (2002
930±60	1010–1220 **1110**	Beta-133809	Stump in growth position	Wiles et al. (2002)
970±60	970–1210 **1080**	Beta-133810	Stump in growth position	Wiles et al. (2002)
450±70	1390–1640 **1480**	Beta-147585	Roots between two tills	Wiles et al. (2002)
370±60	1430–1650 **1540**	Beta-122429	Stump in outwash	Wiles et al. (2002)
320±50	1460–1650 **1560**	Beta-133811	Stumps in outwash	Wiles et al. (2002)
Chisana Glacier 300±50	1460–1670 **1580**	Beta-122426	Log buried in till	Wiles et al. (2002)
Tebenkof Glacier 1460±70	430–670 **580**	Beta-93991	Log in till	Wiles et al. (1999)
Bartlett Glacier 1385±200	220–1040 **650**	W-318	Log in till	Karlstrom (1964)
Dinglestadt Glacier	439–690 **590**	BGS-1271	Stump between two tills	Wiles and Calkin (1994)
Grewingk Glacier	430–690 **590**	BGS-1278	Exhumed stumps	Wiles and Calkin (1994)
400±60	1430–1640 **1520**	Beta-47838	Log buried in colluvium	Wiles and Calkin (1994)
440±120	1280–1680 **1510**	BGS-1272	Wood in gravels	Wiles and Calkin (1994)
360±70	1430–1660 **1550**	BGS-1273	Log in till	Wiles and Calkin (1994)
Tustemena Glacier	1290–1700 **1540**	L-117	Wood in till	Karlstrom (1964)

Table 1 (*continued*)

^{14}C age (years BP)	Calibrated age range (years AD)	Laboratory number	Description and significance	Reference
Bear Glacier	1300–1370	Beta-47835	Wood in deltaic gravels	Wiles and Calkin (1994)
490±60	1380–1520			
400±50	1430–1530 1540–1630	Beta-39636	Wood in deltaic gravels	Wiles and Calkin (1994)
Yakutat Glacier	660–870	Beta - 95984	Log in lacustrine ediments	Calkin et al. (2001)
1270±50	**750**			
1220±60	690–900	Beta - 95991	Log in lacustrine sediments	Calkin et al. (2001)
	800			
1210±60	680–900	Beta-95992	Log in lacustrine sediments	Calkin et al. (2001)
	890			
1350±80	560–880	Beta - 95993	Log in outwash	Calkin et al. (2001)
	700			
1235±160	660–900	NA	Log in till	Post (written comm.)
	800			
725±220	860–1650	NA	Log buried in stream sediments	Post (written comm.)
	1250			

[a] Ages calibrated using CALIB 5.0.2 (Stuiver and Reimer, 1993; Reimer et al., 2004), Calibrated ages are two sigma, numbers in bold are weighted averages of the probability distribution (Telford et al., 2004). Beta=Beta Analytic, BGS=Brock University, L=Lamont–Doherty, W=University of Washington.

and two of these yielded respective radiocarbon ages of cal. AD 270 and 320. Detrital wood in till at Nizina Glacier gave slightly earlier ages of cal. AD 200 and 210, and the outermost Holocene moraine of Copper Glacier was dated by lichenometry to AD 400.

4.2. Medieval Warm Period (MWP) recession

Evidence for a Medieval Warm Period (MWP) in southern Alaska consists of soil formation and forest growth on many forefields in areas that today are only just emerging from beneath retreating termini. This requires considerable ice margin retraction before the subsequent advances of the LIA. At the Sheridan, Tebenkof and Princeton glaciers, tree-ring chronologies show that forest growth on these forefields was continuous between the 900s and 1200s (Fig. 4). These arguments for a MWP are consistent with direct interpretation of tree-ring-width records derived from long chronologies of living and subfossil wood around Prince William Sound that show elevated tree growth and inferred summer warming between 900–1100 AD (D'Arrigo et al., 2006).

Similar evidence for a MWP from the Wrangell Mountains consists of a ^{14}C-dated alder branch from Nizina Glacier between two tills that suggests ice-free conditions about cal. AD 890; similar evidence from Barnard Glacier in the northern St. Elias Mountains suggests an interval of soil formation in a lateral moraine at cal. AD 1110. Four radiocarbon ages from detrital and in-growth position trees on the forefield of Kennicott Glacier were previously interpreted as evidence of ice expansion during the MWP centered on cal. AD 1100 (Wiles et al., 2002). However, we reassess this conclusion here and note that outburst floods from Hidden Creek Lake could plausibly have killed these trees. This ice-marginal lake drains annually through the terminus of Kennicott Glacier (Anderson et al., 2003) and has been active in recent decades, suggesting that it may have been similarly active during the MWP. We therefore favor this interval as a time not of glaciation in the Kennicott forefield but of increased instability, possibly associated with outburst flooding.

4.3. Little Ice Age (LIA) expansions

The Little Ice Age (LIA) in southern Alaska is well constrained with tree-ring cross-dated glacially killed trees and is sub-divided into early, middle and late phases of activity (Wiles et al., 1999; Barclay et al., 2002). Independent tree-ring-width records of summer temperatures show that each of these three phases was associated with summer cooling (Barclay et al., 2002; Davi et al., 2003).

Early LIA expansions were underway in the coastal mountains between ~ 1180 and 1300 AD at Princeton, Tebenkof, Sheridan, and the non-surging Steller Lobe of Bering Glacier (Fig. 4). No end moraines are preserved from this early LIA phase, suggesting that ice margins were not as advanced as during the subsequent LIA phases.

The middle LIA advances in the coastal mountains occurred between ~ 1600 and 1715 AD with most termini making major advances and, in many cases, reaching their Holocene maxima. Moraine ages show that recession occurred by 1750 and lasted until the late LIA advances that were underway by the 1820s. This last phase of expansion culminated between 1880 and 1900 with major moraines constructed on almost all forefields in the region.

In the Wrangell Mountains, middle LIA advances are the best constrained with tree-ring cross-dates showing five termini advancing into forests between ~ 1630 and 1720 AD (Wiles et al., 2002). Late LIA advances brought many ice margins to their Holocene maxima; however, few buried forests of this age have been recovered, most likely because of the middle LIA advance decimated forefield forests. Since the AD 1800s, retreat has dominated with the exception of a minor mid-20th century episode of moraine building.

5. Climatic significance of glacial record

The glacial record from southern Alaska (Fig. 4) shows two major intervals of glaciation, the First Millennium AD (FMA) expansion and the Little Ice Age (LIA) advances. These two broad intervals of ice expansion are respectively followed by ice retreat during the Medieval Warm Period (MWP) and contemporary warming. This millennial-scale variability, with the strongest ice advances recognized about AD 600 and 1650, is coincident with the millennial cycles recognized in the North Atlantic (Bond et al., 2001) and with other temperature proxy records from Alaska and the Northern Hemisphere (Fig. 5).

Within the FMA expansion, the more interior Wrangell Mountains show advances about cal. AD

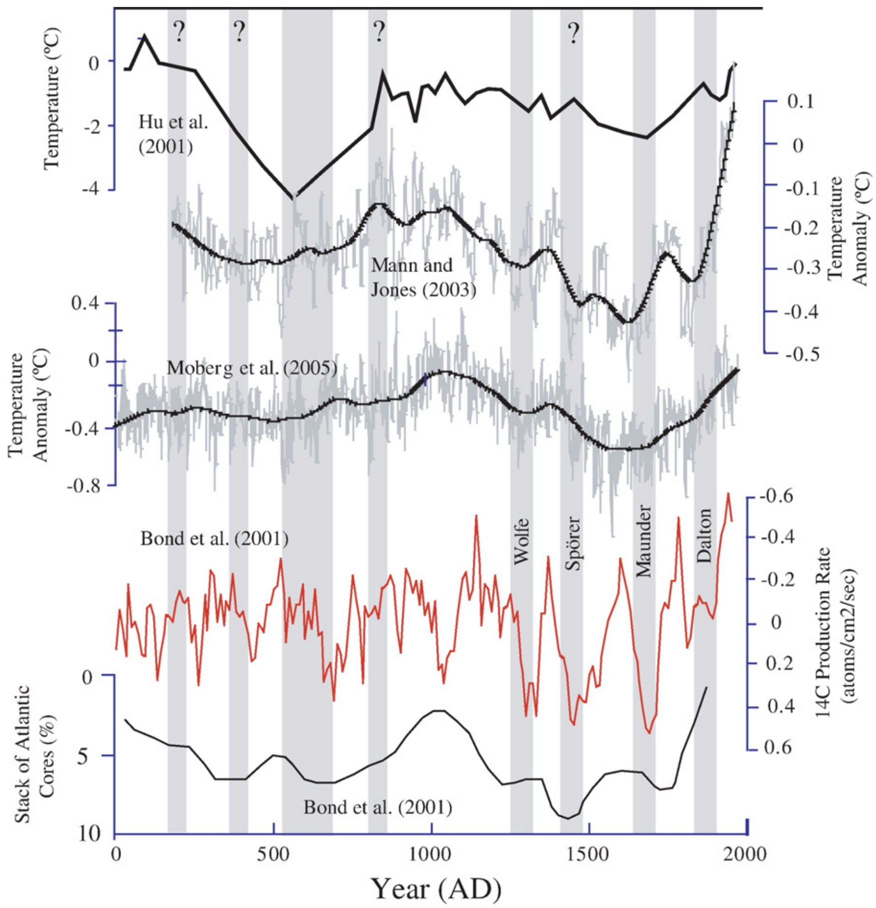

Fig. 5. Compilation of proxy records from the Northern Hemisphere compared with the glacier record from southern Alaska over the past 2000 years. A. Geochemical proxy for temperature from Farewell Lake, Alaska Range (Hu et al., 2001). B. Multiproxy temperature reconstruction for the Northern Hemisphere (Mann and Jones, 2003). C. Moberg et al. (2005) temperature reconstruction for the Northern Hemisphere. D. 14C flux measured from tree-rings as a proxy for past solar irradiance (Bard et al., 1997; as presented in Bond et al., 2001). W = Wolf, S = Spörer, M = Maunder and D = Dalton solar minima. E. Bond et al. (2001) core stack of percentage ice rafted debris for the North Atlantic, the time scale on this record has been shifted back in time by 200 years consistent with the adjustment made by Hu et al., 2003). Note the strongest intervals of glacier expansion at AD 600 and AD 1700 correspond with the lowest temperatures of the first millennium and second millennium, respectively. Both of these times correspond with an unnamed solar minimum about AD 700 and the Maunder Minimum.

200 and 400, in contrast to the coastal sites that show a major interval of advance at about cal. AD 600. Considered with the cal. AD 800 advance of Yakutat Glacier, it appears that there may have been a multi-century structure to the FMA similar to that of the multiple phases of expansion recognized during the LIA (Wiles et al., 2004). This century-scale structure of the FMA was previously suggested from glacial records compiled for Alaska and coastal British Columbia by Reyes et al. (2006). In addition the century-scale structure to the FMA, it appears that the downvalley extent of FMA advances were similar to those of the subsequent LIA.

FMA cooling is consistent with most multi-proxy reconstructions from the Northern Hemisphere and lake and marine records (Fig. 5). Some of these, such as lake sediments from the Alaska Range (Hu et al., 2001) show the interval centered on AD 600 as possibly the coldest period during the past two thousand years (Fig. 5). Similarly, Loso et al. (2006) examined a 1500-year varve record from an ice-dammed lake from the Chugach Mountains near the geographic center of our study. They inferred warm season temperatures from the sediment record and show that the coolest interval was about AD 600. This regional cooling is consistent with a century-scale negative Northern Hemisphere temperature anomaly recently reconstructed by Moberg et al. (2005) and Mann and Jones (2003) (Fig. 5), and is broadly consistent with an increased flux of iceberg-rafted debris to the North Atlantic (Bond et al., 2001). In contrast, Mayewski et al. (2004) did not note this interval as a major cooling event in their comprehensive review of Holocene climate variability based on 50 paleoclimate records.

North Pacific ocean–atmosphere circulation changes are also indicated during the FMA interval. Diatom records from coastal northern California (Barron et al., 2004) suggest a cooling that is consistent with a southward shift in the mean summer position of the Subtropical High at this time (Barron et al., 2004). Isotopic signatures in lacustrine carbonates from the Yukon (Anderson et al., 2005) suggest that the most profound weakening or westward shift of the Aleutian Low over the past 7500 years occurred between AD 300 and 700. This change in circulation would have likely caused both a decrease in winter precipitation and a cooling in southern Alaska; that our glacier records show advance during this time shows that the decadal-scale temperature response of these termini dominated over the effect of diminished accumulation.

Evidence that ice retreated during the MWP is based on soil formation and radiocarbon dates in the Wrangell Mountains at Nizina, Barnard and Kennicott Glaciers as well as from Dingelstadt Glacier on the Kenai Peninsula, and Sheridan Glacier in Prince William Sound and Bear Glacier at Icy Bay (Figs. 1, 4). Termini of these glaciers during the MWP must have been close to or up valley of late 20th century ice marginal positions.

After MWP warmth, land-terminating glaciers in southern Alaska advanced during the early phase of the LIA in the 13th century and then again in the AD 1600s (Fig. 4). Tree-ring records from southern Alaska show regional cooling at both of these times (Barclay et al., 2002; Davi et al., 2003), and Northern Hemisphere temperature reconstructions and North Atlantic ice rafted debris also indicate cooling. However, the magnitude of the 13th century cooling is less than the subsequent temperature drop in the 1600s, and is reflected in the smaller ice advances in during the early LIA relative to the middle LIA expansions.

Ice advance during the late LIA is well documented for the mid to late AD 1800s in all Alaskan regions (Fig. 4). Many of these early to mid-19th century advances brought ice margins to their Holocene maxima (Calkin et al., 2001). Lake records (Finney et al., 2000) and tree-rings (Barclay et al., 2002; Davi et al., 2003) show the early decades of the 1800s expansions as a cold interval in many areas. Since the late LIA advance, glacier retreat has been dominant across southern Alaska except for a minor mid-20th century moraine building event (Calkin et al., 2001; Arendt et al., 2002).

Previous analyses of the glacial record showed a 200-year rhythm to glacial activity in Alaska and its possible link to the de Vries 208-year solar (Wiles et al., 2004). Similarly, high-resolution analyses of lake sediments in southwestern Alaska suggests that century-scale shifts in Holocene climate were modulated by solar activity (Hu et al., 2003). Solar variations have also been proposed as being instrumental in generating moraine building in the Northern Hemisphere (Denton and Karlèn, 1973), affecting temperature changes on millennial timescales throughout the Holocene (Bond et al., 2001), and having linkages to North and Central American drought (Yu and Ito, 1999; Hodell et al., 2001).

For the Little Ice Age, a significant decrease in solar irradiance at the start of the Wolf solar minimum corresponds with glacier expansions starting about AD 1250 (Figs. 4 and 5). There is little evidence for termini advancing in Southern Alaska during the Spörer Minimum centered on AD 1450; however, the glacial record from the high Arctic Brooks Range shows the strongest peak of the last 1000 years during this interval (Evison et al., 1996; Wiles et al., 2004). The Maunder solar minimum, the most intense of the set of named minima during the second millennium AD, corresponds with the mid to late 17th century peak in glacial activity and was probably the coldest interval of the last millennium based on the glacial record and Northern Hemisphere temperature reconstructions (Fig. 5). The late LIA glacial advances closely followed the Dalton solar minimum (Fig. 5).

Modeling efforts (Braun et al., 2005) suggest that the 1470-year cycle observed in North Atlantic ice rafted debris is due to the superposition of the shorter solar cycles of 87 and 210 years and their influence on thermohaline circulation. The 210-year cycle is evident in the glacial record from the North Pacific, and its intensification through meltwater flux and modulation by the 87-year cycle may be linked to the millennial-scale variability recognized in proxy records.

Analysis and interpretation of other composite glacial records are similar to our results for Southern Alaskan. Significant intervals of advance during the FMA and LIA are recognized from termini in the coastal and interior montane regions of Canada (Luckman, 2000; Reyes et al., 2006), and links to solar variability have been made with glacier and tree-ring records from the Canadian Rockies (Luckman and Wilson, 2005). In west-central Europe, the Great Aletsch, the Gorner and Lower Grindelwald glaciers in the Swiss Alps all made strong advances to near LIA limits about AD 600 and have a 200-year structure to the LIA expansions (Holzhauser et al., 2005).

6. Conclusions

Land-terminating glaciers in Southern Alaska provide records of past temperature variability for the past 2000 years. General glacier expansions during the First Millennium AD (FMA) in Southern Alaska occurred at cal. AD 200, 400 and 800 with the strongest advance at cal. AD 600. Many records suggest the ice extent at this time was as extensive as subsequent Little Ice Age (LIA) expansions. Ice recession during the Medieval Warm Period (MWP) is suggested for glacier forefields based on soil development and forest growth on the glacier forefields in Southern Alaska. High precision tree-ring dated glacier histories for the last millennium show that the LIA comprised three distinct phases of expansion.

The FMA-MWP-LIA alternation is consistent with millennial-scale records of ice-rafted debris flux in the North Atlantic and Northern Hemisphere temperature reconstructions. Variable Holocene solar irradiance has been proposed as a potential forcing mechanism for millennial-scale climate change, and this is supported by the Southern Alaskan glacial record.

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